

Note on Low Energy Positron/Electron Accelerators as an Absolute Energy Calibration Source.

Milind Diwan, Kirk McDonald

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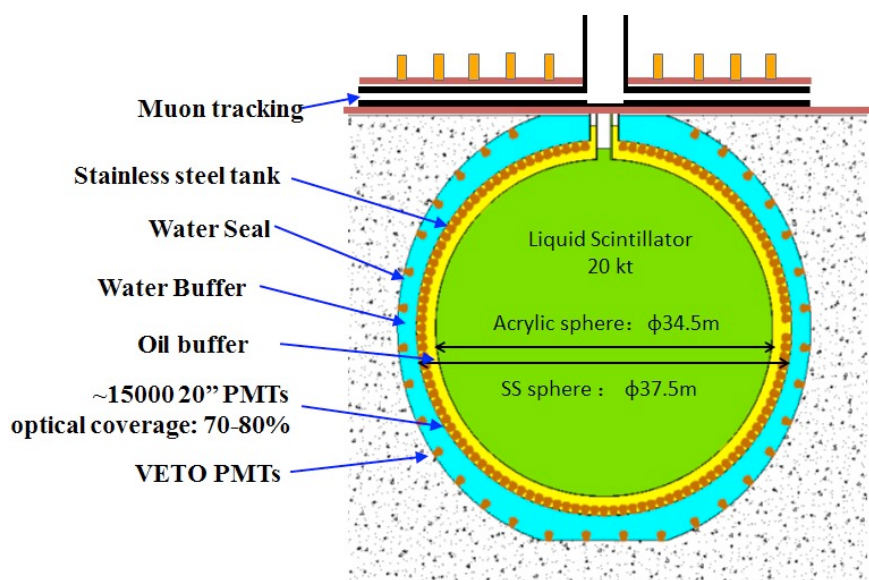
DRAFT 2

Introduction

These notes were assembled to summarize our current understanding of the requirements regarding absolute calibration of the JUNO liquid scintillator detector. The emphasis is on requirements regarding deployment of an accelerator based calibration system. The notes are based largely on existing information from the exercise carried out by the Superk collaboration in 1996-1997. Superk obtained $\sim 1\%$ calibration by the use of a low energy LINAC (5-16 MeV/c) for electrons. This represents existence proof that such a system should work. JUNO requirements are somewhat different both due to the need for positrons and the geometry of the detector.

We attempt to assemble as many facts, and requirements as we can collect so that a proper evaluation of

different proposed technologies for the calibration accelerator

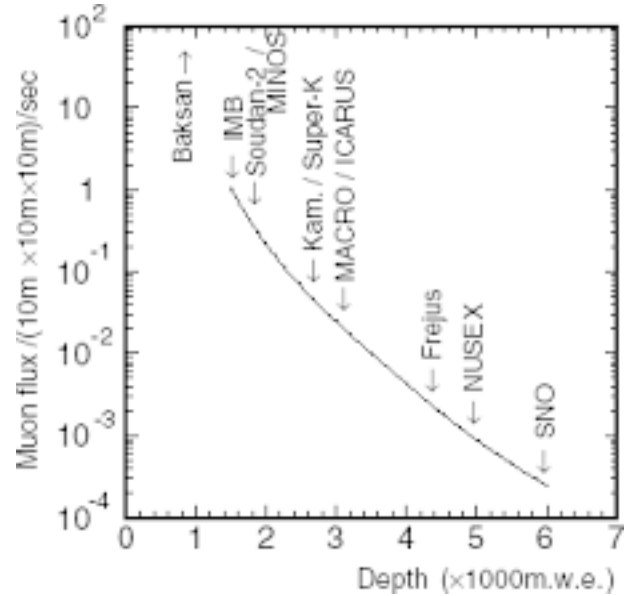


can be evaluated. We also note down what is not known and might require R&D.

Assumptions

- i. Detector will be liquid scintillator with dimensions of a sphere of approximately 35 m, and fiducial mass of 20 kt.
- ii. Detector will be read out with ~15000
20 inch diameter photo-multipliers with optical coverage of 70-80%.
- iii. Detector will be located 600 meters underground with a muon rate of $\sim 10^{-3}$ Hz/m²
- iv. The sphere of liquid scintillator is contained in either options 1) an acrylic sphere with PMTs out of the acrylic or 2) a transparent balloon.
- v. The access to the inside of the sphere is obtained through a neck of unspecified dimensions.
- vi. The deck about the sphere may have muon detectors such as RPC, and has unspecified utilities and access. Other uses of the deck are as yet to be determined.
- vii. Accelerator calibration should take no more than 1 month for each year of data-taking. 1 month corresponds to $\sim 10^6$ sec of actual running time.
- viii. The calibration should be performed immediately after establishment of stable physics running.

Scientific Requirement



Achievement of 3-4 sigma rejection of the wrong mass hierarchy in a few years requires both excellent energy resolution and excellent energy scale uncertainties. With the expected statistics from ~ 35 GW (thermal) reactors at 53 km, the following is needed:

A. Energy Resolution $< 3\%/\sqrt{E}$ over the entire volume. Zhan, PRD79:

073007(2009).

B. Energy Scale uncertainty to be controlled $< 1\%$ over entire volume. Arxiv: 1208.1551

Detector Requirements

Signal: Event signal consists of a positron of 0 to ~ 10 MeV that come from Inverse Beta Decay (IBD) which has threshold of 1.8 MeV of anti-electron neutrino energy. The positron annihilates after depositing all its kinetic energy. The annihilation photons are also detected as energy of 1.022 MeV.

Source Based Calibration: Daya Bay Collaboration used the following sources for detector calibration.

Mono-energetic Photon Lines

Radioactive sources regularly deployed: Ge68 (positrons), Co60 (1.17 MeV, 1.33 MeV), Am241-C13 (?),

Radioactive sources during special runs: Cs137(0.662 MeV), Mn54(0.835 MeV), K40(1.460), Am241-Be9 (?), Pu-C13(?)

Radioactivity from regular data (from detector materials and contamination):

K40(1.460), Ti208(2.62 MeV), n capture on H (2.2 MeV)

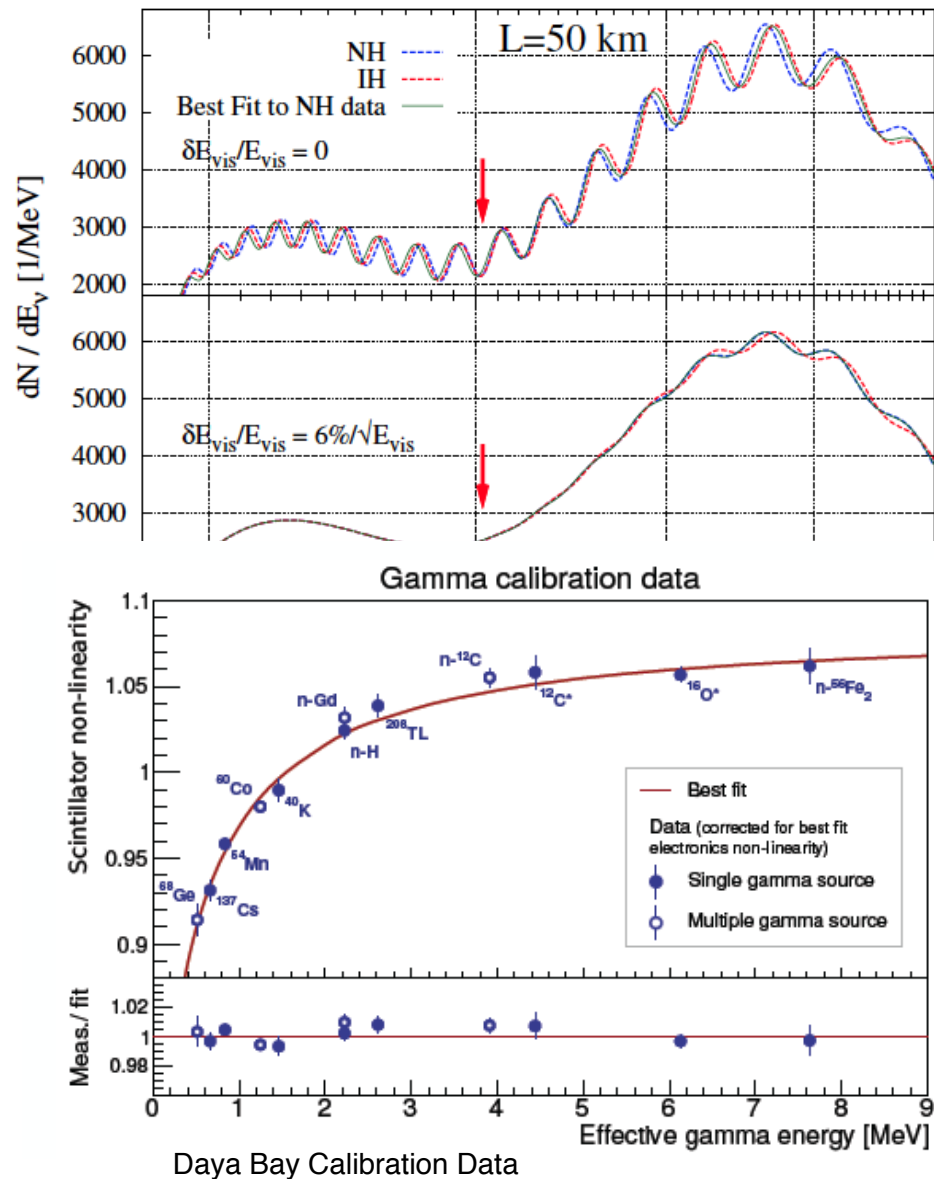
Beta decays by muon spallation:

B12 from muon spallation continuous beta spectra up to 14 MeV.

Alpha decays:

Po212, Po214, Po215

Accelerator based calibration will require a mono-energetic positrons of well known kinetic energy deposited in a well-determined location in the fiducial volume of the detector. The energy of the positron will be varied between 1 to 10 MeV during the calibration. An event sample of $\sim 10^5$ reconstructed positron calibration events is needed at each calibration energy. Single positrons of selected energy well-separated in time from other particles are needed for calibration.



Signal Characteristics

Positrons of energy 1-10 MeV have a characteristic range of 0.5 cm to several cm in the liquid scintillator detector. The signal yield is expected to be ~ 1200 photo-electrons per MeV. Most of this light is isotropically distributed and detected in 15000 PMTs. Approximately 10% of the PMTs are expected to have a signal for a typical event. Time of PMT hits, and intensity of light will be used to determine the location of the positron and associated corrections due to absorption, scattering, and any geometrical effects.

Beam Transport System

The beam transport system must deliver approximately 10^5 positrons of a given energy with $\Delta p/p < 1\%$ at a selected location in the detector fiducial volume. The average number of positrons should be ~ 1 positron per unit time where unit time will be defined by the characteristic time of the readout electronics. Typically < 1000 Hz is preferable with high duty factor. A minimum of ~ 10 Hz are needed to satisfy the assumption that beam calibration has 10^6 sec allocated.

The Beam Transport System will include appropriate collimators and magnets to select momentum so that both the intensity and momentum bite for the particles into the detector can be tuned. The system of collimators and momentum selection will result in reduction of intensity from the accelerator by factor of 10^3 to 10^6 .

Geometry of the JUNO detector restricts the calibration position to be along the vertical axis of the detector which can be accessed by placing a beam-pipe through the neck of the spherical acrylic tank. *If off-axis locations for calibration are required the considerable investigation is needed to design the neck of the detector so that a beam pipe can be oriented to reach these locations.*

The Beam Transport System should include appropriate monitoring devices to detect the positron exiting from the beam system and into the detector. These monitoring devices may be fixed or removable.

The Beam Transport System window through which the positrons will exit into the detector will need to be of thin, low density, low atomic weight material to reduce absorption and scattering and also allow accurate determination of energy entering the detector.

The Beam Transport pipe into the detector must be shaped so that it presents a minimal shadow ($< \text{few } \%$) to the scintillation light.

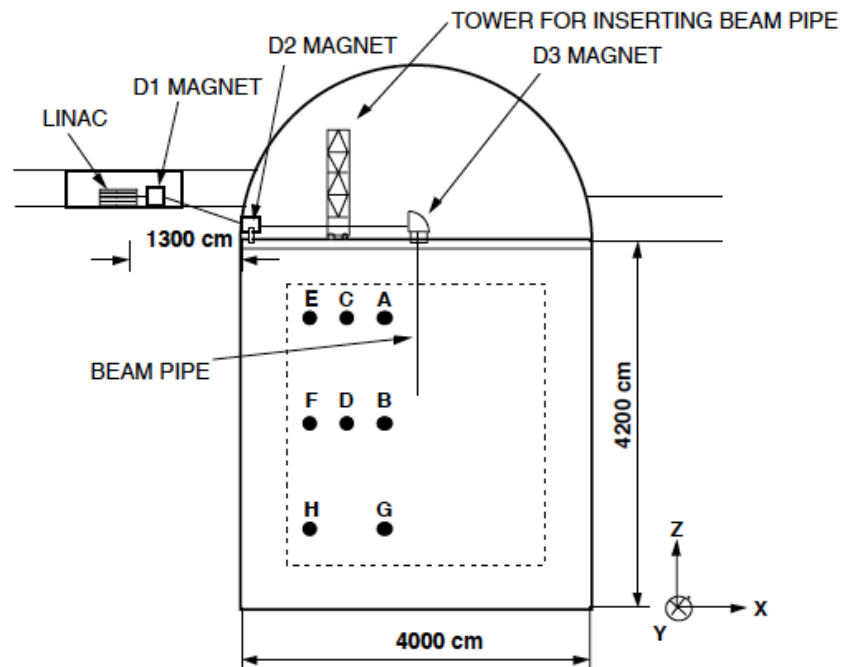
The materials of the beam transport pipe must be tested for compatibility with liquid scintillator. This includes the window material.

Additional monitoring devices on the Beam Transport System are to detect unexpected losses of beam particles and respond appropriately.

The low momentum of the beam requires careful consideration of stray magnetic fields in the underground area. It may need to be mapped and beam pipe may have to be covered by Mu-metal shielding.

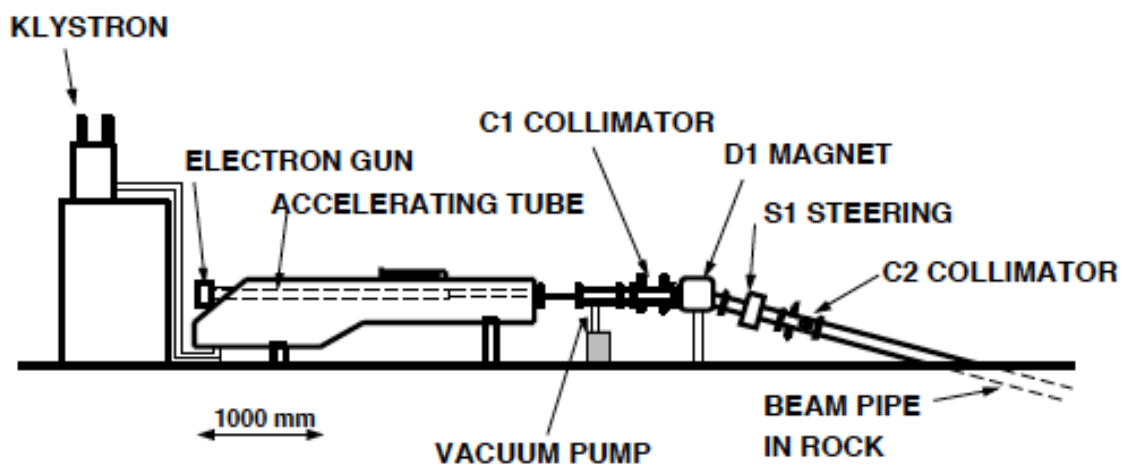
The Beam Transport System loss must not exceed the allowable radiation limits at the deck. These limits may be derived from considerations of allowable shielding, safety, allowable background count rate in the detector.

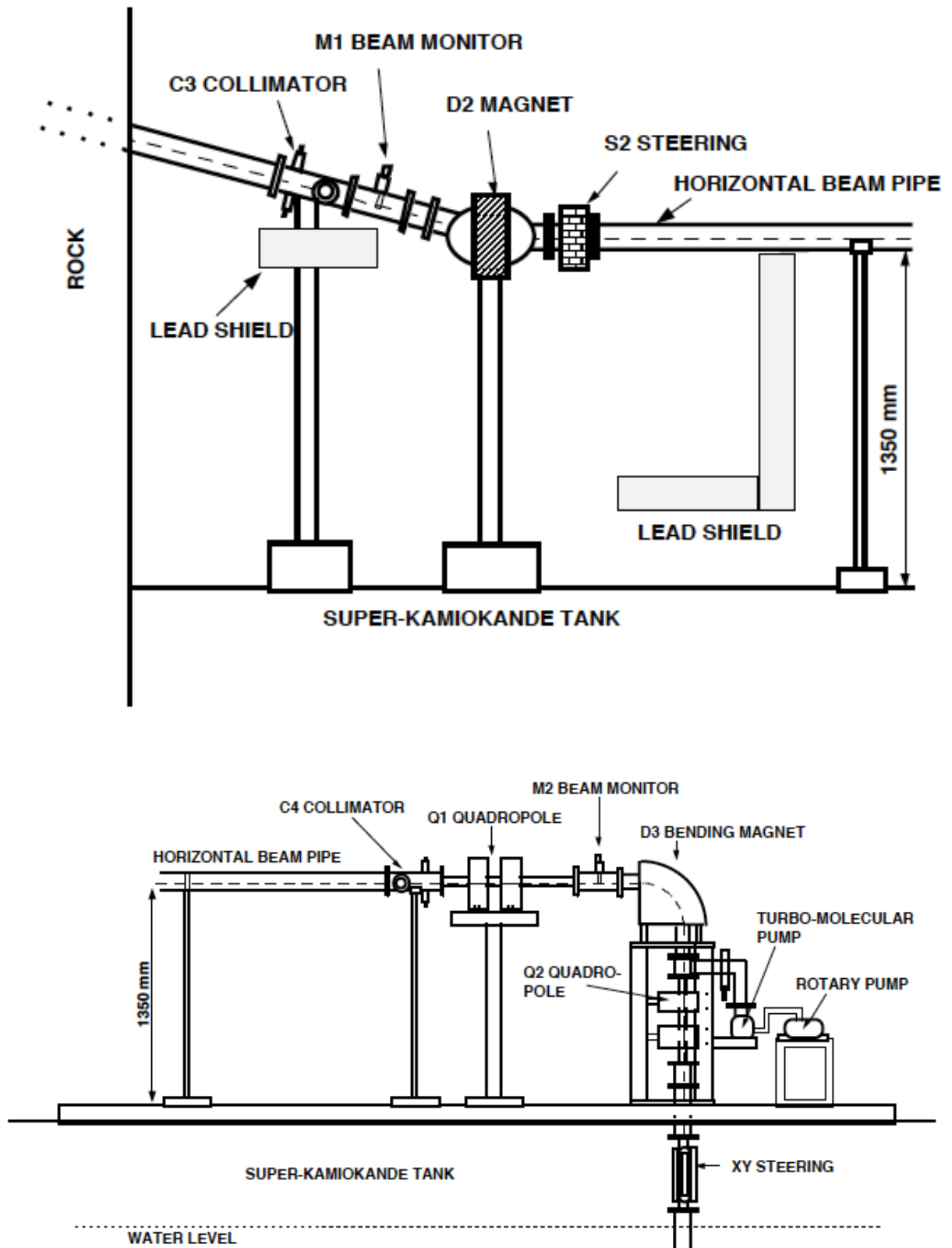
The Beam Transport System will consist of vacuum pipes, collimators, dipole and



quadrupole magnets, positioning systems and stands, shielding, vacuum systems, fast valves, radiation monitors, electrical power and cooling.

The SuperK beam transport schematics are included.





Facility Systems Related to the Beam Transport System

These requirements are initial estimates using SuperK experience as guidance.

Deck Space: $\sim 30 \text{ m}^2$ of space on the deck will be needed for beam transport systems.

A system for raising the beam insertion will be required with appropriate height of $\sim 10 \text{ m}$.

Neck access: Access will be needed through the neck for the accelerator beam-pipe.

This must be planned in advance since there are many other services that will be utilizing this space.

Power: Power will be needed for < 10 magnets, collimators and other energized systems. Vacuum will be needed for beam pipe of ~ 50 meters in length with \sim few cm diameter.

Water: Cooling water will be needed.

Permanence: The beamline on the deck will most like be used over a course of no more than a few months integrated over several years.

Storage: The beamline elements inserted into the liquid scintillator detector must be removed and stored. Storage facility will be required underground for this beam-pipe and other spare parts for maintenance of the beam-line.

Shielding: There must be adequate shielding to eliminate any correlated radiation from the accelerator and beam transport to the detector. There may have to be separation of the accelerator system from the detector using rock. (see SuperK design).

Accelerator System and Source

Acceleration system and the source will produce a tunable energy (1-10 MeV) beam of positrons that will be transported to the detector by the beam transport system. The intensity of 10^3 to 10^6 per second at a rate of 10 - 1000 Hz with preference for the higher duty factor.

Accelerator system Parameters		
Source	Positron Source. < 10	We want to keep the source strength relatively low so that it can be handled without too much difficulty.
Source lifetime	> 50 yrs	We do not want a short lived source.
Beam Momentum	1-10 MeV/c	
Pulse width	~CW	high duty factor (>1%) is preferred
Repetition rate	10 - 1000 Hz	Essentially CW referred.
Maximum intensity/pulse	$\sim 10^6$	This depends on the duty factor achieved.
Beam size	~few mm	Anything larger is not needed
Beam angular spread	~few mrad	smaller is better
Vacuum	10^{-7}	Nothing special is needed
Power	average power <1000 watt	Can it be kept low ? Any lower makes no sense since other systems will require just as much power.
Size	< few meters in any dimension	Any larger will require large underground excavation.

Accelerator system parameters are shown in Table with some initial design guidance with justification.

Facility Systems Related to the Accelerator Systems:

Underground space: Approximately $\sim 50 \text{ m}^2$ of underground space will be needed in proximity of the liquid scintillator detector deck for the positron accelerator and associated systems. The length, width, and ceiling height will need to be determined based on the accelerator technology. It may be preferable to locate the accelerator some distance away from the deck through the rock to eliminate any background radiation from reaching the detector. The thickness of this rock need not be more than a \sim few meters.

Power: Power will be needed for the RF systems, vacuum, magnets, and any cooling systems. Total power consumption should be kept low with average of $< 1 \text{ kw}$ (?) as guidance.

Water: Water is needed for cooling of various systems.

Permanence: The accelerator will most likely be used over a course of no more than a few months integrated over several years.

Storage: Storage is needed for small diagnostic items and maintenance for the accelerator.

Shielding: There may have to be separation of the accelerator system from the detector using rock. (see SuperK design). The beam-line may have to go through rock to the deck to eliminate direct background from the accelerator.

Beam Energy Calibration

Provision must be made to calibration the energy of the injected positrons with respect to the magnet settings independently of the liquid scintillator detector. This may involve reconfiguration on the deck requiring more space on the deck.

R&D needed

1. The positron source will need R&D to reduce the source strength and improve efficiency.
2. The beam window in the detector will require R&D to reduce the thickness and reduce shadowing, reflection, etc.
3. R&D is needed for calibrating the energy that is deposited in the detector. For example, what is the ideal geometry for deploying a Ge detector in the beamline.
4. Accelerator R&D to reduce the beam intensity and maintain diagnostics and control.
5. Reduction of power for all underground systems.

Safety

1. Insertion and removal of the beam pipe in the detector presents multitude of challenges. This operation must be integrated in the design.
2. Vacuum window (inside the detector) materials, thickness must be carefully engineered.
3. Protection of the accelerator systems requires fast vacuum valves in case of window breaks.